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# REVIEW ON NPK SENSOR USED ON SOIL

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***Review Paper***

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## ABSTRACT

This review article discusses the importance of soil fertility in agriculture and the role played by NPK (Nitrogen, Phosphorus, and Potassium) in plant growth. It explores a few NPK sensor technologies utilizing electrochemistry, optics, capacitors, and biosensors for soil monitoring in real time. The article mentions developments with IoT-based smart farming, augmenting precision agriculture as well as eco-sustainability. Various studies and various sensor models have been read and studied to confirm their accuracy and effectiveness as well as their limitations. Future studies focus on sensor longevity, AI training, and multi-sensor fusion for increased precision farming.

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**Keywords:** NPK sensors, Soil nutrient monitoring, Precision agriculture, Smart farming , IoT in agriculture, Electrochemical sensors , Optical soil sensors , Capacitive soil sensors , Biosensors , Real-time soil analysis, Fertilizer optimization , Soil fertility management , Sensor calibration , Wireless sensor networks (WSN) ,AI in agriculture.

## INTRODUCTION

As the main substrate for plant growth and nutrient absorption, soil is the cornerstone of agriculture. Its fertility directly affects agricultural output and establishes the general health of crops. Essential macronutrients, organic matter, helpful microbes, and a balanced pH level are all found in healthy soil, and they all support the best possible plant growth. The three main macronutrients that are essential for soil health and plant growth are nitrogen (N), phosphorus (P), and potassium (K). To maintain soil fertility and guarantee excellent crop yields, these nutrients—collectively known as NPK—are frequently added through fertilizers. Each of these macronutrients has a distinct function in soil fertility and plant physiology, and balanced growth depends on the soil's ideal concentration of each:

As a crucial building block of proteins, amino acids, and chlorophyll, nitrogen (N) is necessary for photosynthesis, leaf development, and vegetative growth. For the best plant growth, soil should contain between 20 and 50 mg/kg (parts per million, or ppm) of nitrogen, while the exact amount needed depends on the type of crop. While too much nitrogen can create an imbalance and encourage too much foliage at the expense of fruit or grain production, too little nitrogen causes stunted development and yellowing of the leaves.

**Phosphorus (P):** A key component of ATP (adenosine triphosphate), phosphorus is essential for energy transfer in plants. It encourages the growth of roots, flowers, and seeds. For the majority of crops, the optimal soil phosphorus concentration is between 10 and 20 mg/kg (ppm). However, because phosphorus tends to interact with soil minerals and reduce plant accessibility, its availability is frequently restricted. Early plant growth and increased resistance to environmental stress depend on effective phosphorus management.

**Potassium (K):** Potassium is essential for water homeostasis, enzyme activity, and disease and

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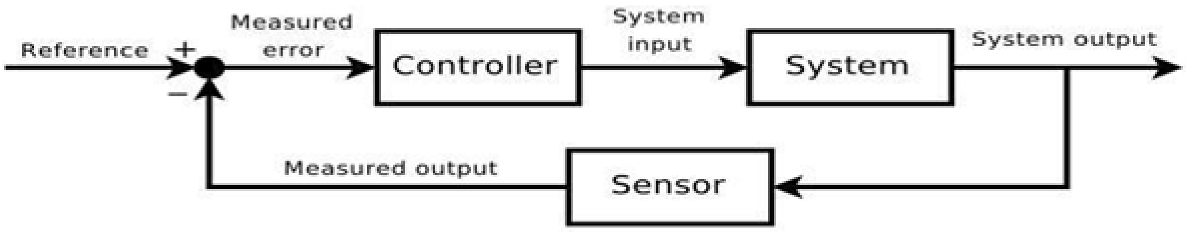
environmental stressor resistance, including drought. It promotes nutrient uptake, fortifies plant cell walls, and raises crop quality overall. Depending on the needs of the particular crop, the necessary potassium content in soil is typically between 100 and 200 mg/kg (ppm).

For sustainable farming methods and maximum crop yield, it is essential to keep a balanced ratio of these nutrients in the soil. However, real-time monitoring is required because traditional soil testing techniques are frequently labor-intensive and time-consuming.

NPK sensors have been created for real-time soil fertility monitoring in order to improve fertilizer application and handle the issues of nitrogen imbalance. Farmers can apply fertilizer more intelligently thanks to these sensors' accurate assessments of nutrient amounts. By limiting nutrient runoff and soil degradation, they help to improve crop yield and environmental sustainability by preventing excessive or insufficient fertilization.Electrochemical sensors – Employ ion-selective electrodes to determine and measure the concentration of specific ions of nitrogen, phosphorus, and potassium in the soil.

Optical sensors – Use spectroscopic methods like near-infrared (NIR) and fluorescence spectroscopy to measure light absorption patterns and calculate nutrient content.Capacitive and dielectric sensors – Detect changes in soil permittivity, which are related to ion concentrations, and thus reflect soil moisture and nutrient levels. Biosensors – Employ biological elements such as enzymes or microorganisms to facilitate highly specific detection of NPK components through biochemical reactions. Modern agriculture is changing as a result of precision farming methods combined with NPK sensors. These sensors maximize agricultural yields, lower expenses, and optimize resource use by enabling site-specific fertilization. Furthermore, NPK sensors can be included into automated soil monitoring systems thanks to developments in Internet of Things (IoT) technology, which expands the potential of smart farming.

Analyzing the function of NPK in soil fertility, developments in NPK sensor technology, and their uses in contemporary agriculture are the goals of this review study. This study intends to offer important insights into effective soil nutrient management strategies by combining recent advancements and technological breakthroughs. The significance of reviewing the papers for implementing it on hardware for future studies. This is also beneficial for farmers such as Increased crop yield , Cost-effectiveness , Environmental Sustainability and integration with Smart Farming.




The above block diagram shows precision agriculture can use this closed-loop control system and to ensure ideal soil nutrient levels, the controller modifies fertilizer application based on real-time NPK sensor data. The controller receives feedback from the sensor's continuous monitoring of soil fertility, reducing variations from the target nutrient levels. This automated system encourages sustainable farming methods, improves crop growth, and uses less excess fertilizer.

**LITERARURE REVIEW**

Mohanty, S. [1] et al proposed that Smart agriculture uses IoT, AI, and fog computing to enhance the utilization of resources and yield of crops. This study suggests a fog-assisted recommendation system for forecasting soil moisture and NPK content using hybrid machine learning algorithms on the IFogSim platform. The method improves the quality of the soil, irrigation efficiency, and stability and decreases soil erosion. It also finds use in the mining industry for structural protection and slope stabilization.

Musa, P. et al [3] proposed that the study developed a digital monitoring system for measuring NPK , and soil humidity using Arduino Nano and JXCT NPK sensor. Findings indicate accuracy of 80% in detecting NPK and optimal soil moisture in three sawahs. Analysis of soil content of fertilizer elements indicates fluctuation between sawahs, with sawah 2 exhibiting highest nitrogen and kalium levels. The system is expected to assist farmers to manage land more efficiently and enhance rice productivity.

Musa, P. et al proposed thatthis research investigates how Wireless Sensor Networks (WSNs) can be utilized in NPK macronutrient monitoring to boost agricultural yields. The research looks into types of sensors, where sensors are placed, wireless communication, and transmission rate for precision agriculture. The research identifies an error rate of 8.47% in NPK sensor readings relative to laboratory results, signifying dependable performance. Future breakthroughs will seek to maximize yields and facilitate the cultivation of crops across varied points of location.

Kumar, L. L. et al [4] proposed that this project designs a soil NPK sensor with an Arduino board and OLED display to monitor nitrogen, phosphorus, and potassium in real-time. The sensor supports farmers in optimizing soil fertility and productivity by providing accurate monitoring of nutrients. Measurement is done through a probe, processed on the Arduino, and read for visibility. The technology supports precision agriculture, providing an easier and quicker alternative to manual soil testing techniques.

Adhikary et al [5]proposed thatthis research introduces a new neural network method to enhance the precision of agricultural parameter estimates from sensor measurements, accounting for external variability. The model performs better than conventional techniques in predicting soil moisture and nutrient content under varied conditions. Multi-site real-time data confirm its utility for precision agriculture. Future work will incorporate deep learning and edge computing to scale up and improve real-time response.

Fauziah et al [6] proposed that This research investigates the potential of IoT in soil nutrient analysis for smart agriculture, with existing challenges and potential future applications. A bibliometric review of 395 papers found gaps in mass validation and standard agricultural practices. Results indicate the majority of nutrient management systems are still in the prototype phase without plant testing validation. Future work on IoT-based NPK sensors seeks to increase agricultural efficiency and farmer accessibility.

Amado et al [7] proposed that This research employs cutting-edge sensors, such as an ISFET pH sensor, soil moisture sensor, and RGB color sensor, to improve soil nutrient tracking. Coupled with an Arduino MEGA 2560, these sensors report real-time soil characteristics. Machine learning processes over 300 soil samples to estimate nitrogen, phosphorus, and potassium content. This method enhances precision agriculture by maximizing soil management and nutrient management.

Cheruvu et al [8] proposed that his article describes the implementation of IoT-based smart agriculture for increasing productivity and resource use. The system monitors real-time soil nutrients, temperature, humidity, and moisture through sensors. A recommendation system recommends the most suitable crops based on sensor readings, allowing farmers to make decision-making easier. This efficient and easy-to-implement system optimizes farm methods for food requirements in the future.

Ivan Lionel et al [9] states that this research tests the precision and specificity of sensors in determining soil NPK nutrient levels in accurate fertilization. Analyses with various NPK compounds found the sensor not very specific, reading unintended components. The regression analysis indicated high correspondence ($R^2 \approx 1$) due to dependence on the electroconductivity method. The sensor did not also distinguish between various NPK fertilizer concentrations, which demonstrates the necessity for better measurement methods. In January 2020, Akriti Jain et al [10] proposed that this study employs a TCS3200 color sensor to measure nitrogen (N), phosphorus (P), and potassium (K) content in soil for better fertility control. The sensor examines light absorption and reflection to conclude nutrient levels, with the information being processed by a NodeMCU microcontroller. In contrast to conventional liquid-based NPK kits, this process operates directly on solid soil samples for improved suitability. The system is designed to advance future farming by allowing accurate and affordable nutrient control.

| **Paper Title** | **Sensor Type** | **Measurement Principle** | **Calibration Method** | **Limitations** |
|---|---|---|---|---|
| Sachin Chandravadan Karad's [11] | Optical-electrical, Wireless, NMR-based | Optical sensing, Wireless IoT monitoring, NMR-based spectroscopy | Field calibration through LED-based detection | High cost of NMR sensors, Wireless connectivity issues |
| Munezero Alphonse et al [12] | IoT-Enabled Soil Sensors | ML-based Fertilizer Prediction | AI-based optimization | Model performance depends on data quality |
| Misbah et al [13] | Remote Sensing (Hyperspectral, Multispectral) | Imaging spectroscopy for soil and crop nutrient mapping | Machine learning-based calibration | High computational requirements |
| Sana Tatli et al [14] | Electronic Nose (MOS Gas Sensors) | VOC emissions analyzed with statistical models | Multiple regression models (PLSR, PCR, MLR) | Less accurate for P and K, affected by plant metabolic variations |
| Darmawan et al [15] | Electrical (Capacitive & Conductive) | Conductivity and Capacitance correlation with NPK levels | Linear regression analysis | Affected by soil moisture levels, requires combination of multiple parameters |
| R. Madhumathi et al [16] | Color Sensor, Photodetectors | Colorimetry | MATLAB-based calibration | Limited accuracy due to environmental factors |
| Akande et al [17] | pH Sensor, Soil Moisture Sensor | pH-based NPK Approximation | pH-NPK Correlation Chart | Accuracy depends on pH estimation |
| Potdar et al [18] | Optical (Spectroscopy, Colorimetry) | Reflectance, Absorption, and Transmission Spectroscopy | Comparison with standard lab methods | Environmental factors affect accuracy |

HaristianPratama et al [19] states that this research employs an NPK sensor with NodeMCU to sense nutrients in soil and report data to ThingSpeak for convenient monitoring. The system assists citrus seedling farmers in maximizing growth by offering real-time nutrient testing. In a test, wet soil was found to contain more nutrients, with the sensor attaining 90% accuracy.

Bhatnagar et al [20] states thatthe proposed study is on a wireless system to measure real-time soil NPK levels, obviating the lag associated with conventional lab analysis. It enables farmers to read soil nutrients directly on their Android mobile phone. This ensures no nutrient shortages and lessened possible economic loss.

Reis et al [21] proposed that this research assesses the evolution of NPK sensors for precision agriculture based on an analysis of 95 patent documents. Results indicate that 66% of sensors are applied in both soil and bio-management, with China dominating patent filings (96%), especially in Jiangsu. The study emphasizes the importance of innovation in maximizing fertilizer use and crop yields.

Madhumathi et al [22] states that precision agriculture leverages IoT and colorimetry to analyze soil nutrients and optimize fertilizer application. A fuzzy expert system with Mamdani inference rules recommends precise nutrient quantities, with data processed in MATLAB and sent to ThingSpeak. This system enables farmers to monitor soil health via a mobile app, promoting efficient green farming.

Tolentino et al [23] states thatthis research develops a digital single-probe sensor to simultaneously monitor soil NPK, temperature, moisture, and pH. Using electrical conductivity and resistivity, the probe determines nutrient levels, with reagents enhancing accuracy. A Wi-Fi module enables real-time monitoring, with the device showing a 12% error in soil fertility assessment.

Jain et al [24] proposed thatthis study employs a TCS3200 color sensor to measure soil NPK content through light reflection and absorption analysis of solid soil samples. The reflected light is converted into frequency signals by the sensor, which are then processed by a NodeMCU microcontroller for nutrient evaluation. This approach provides a more practical and affordable solution compared to liquid-based NPK kits for precision agriculture.

Dacay et al [25] states this research enhances the "NPK-lyzer," an optical transducer device that measures soil NPK content with LEDs and a photodiode sensor. Experimentation revealed its reliability in meeting Department of Agriculture laboratory results, detecting low nutrient content in soil. An app on a smartphone allows users to scan and track soil nutrient information easily.

Phong et al [26] statesthis research mimics nutrient distribution in farm soils with soil electrical conductivity (EC) fluctuations simulated by a convection-diffusion equation. COMSOL software precisely forecasts ion transfer from NPK fertilizers, with RMSE ranging from 0.001 to 0.048. The model helps optimize fertilizer application to reduce environmental footprint.

Nair et al [27] proposedthis research investigates the application of MEMS-based cantilever beam sensors for NPK nutrient detection in soil via localized heating due to light absorption. The sensor has high sensitivity and miniaturization into optoelectronic devices. The method helps determine soil fertility for better crop development.

| **Paper Title** | **Sensor Type** | **Measurement Principle** | **Calibration Method** | **Limitations** |
|---|---|---|---|---|
| HaristianPratama et al [19] | NPK Soil Sensor | Measures soil nutrient content and transmits data via IoT | Requires manual calibration for accuracy | Limited battery life of IoT devices |
| Bhatnagar et al [20] | Electrochemical (ISFET, ISE) | Ion absorption & electrochemical reactions | Comparison with soil nutrient standards | Short lifespan of sensors, need for frequent calibration |
| Reis et al [21] | Various (Optical, Electrochemical, Wireless) | Patent mapping study on existing NPK sensors | Not applicable | Lack of standardization in sensor technology |
| Madhumathi et al [22] | Colorimetric sensor | Light transmission and detection for NPK concentration measurement | Uses fuzzy logic-based inference for calibration | Colorimetric analysis may be affected by soil texture and external factors |
| Tolentino et al [23] | Single Probe NPK Sensor, pH Sensor | Electrical Conductivity | Direct calibration with soil samples | 12% error in soil fertility detection |
| Jain et al [24] | Optical (Color Sensor) | Light absorption and reflection using color sensor TCS3200 | Standard absorption wavelengths comparison | Accuracy affected by soil conditions |
| Dacay et al [25] | Optical (LED-Photodiode System) | Optical transducer with wavelength detection | Comparison with Department of Agriculture soil lab dat | Limited to qualitative nutrient assessment |

| | | | | |
|---|---|---|---|---|
| Phong et al [26] | Electrical Conductivity (EC) sensor | Simulation of ion movement in soil using EC variation | Validation through experimental monitoring of soil EC | Does not directly measure NPK, relies on EC correlation |
| Nair et al [27] | MEMS Sensor | Miniaturized sensor for detecting NPK levels based on microelectromechanical technology | On-site calibration with standard soil samples | Sensitivity to environmental variations, initial calibration required |

Coutinho et al [28] states this research analyzes the effect of soil sample preparation on NPK content analysis through Vis-NIR and Mid-Infrared spectroscopies. Vis-NIR spectroscopy demonstrated improved predictive performance with drying temperature and soil particle size not having a significant impact. Yet, high prediction errors would restrict its application in variable-rate fertilizer application in precision agriculture.

Monteiro-Silva et al [29] states this work investigates a small, modulated sensing system based on UV-Vis spectroscopy and optical fibers to measure NPK in fertilizing water. Severe spectral interference was addressed using an AI self-learning algorithm, which provided robust nutrient prediction. The results validate real-time NPK monitoring for micro-irrigation systems.

Nameesha Chauhan et al [30] states this study examines soil macronutrients and the impact of *Azadirachta indica* extract as an organic fertilizer. The extract enhances the fertility of the soil, reduces the amount of nitrogen runoff, and reduces the use of chemical fertilizers. Electrochemical sensors quantify nutrient content, allowing for sustainable agriculture.

Masrie et al [31] states this project establishes an optical sensor-based system for detecting soil macronutrients (NPK) through LED transmission and photodiode detection. The intensity of the nutrients is determined by their light absorption, and signal amplification for measurement. Results show absorption response voltages of 32.0V for Nitrogen, 4.6V for Phosphorus, and 19.8V for Potassium.

Liu et al [32] states new MEMS-based chip-level colorimeter was designed for high-accuracy NPK detection in soil. It has a low-cost, compact design with reduced error, surpassing commercial colorimeters. This technology improves precision agriculture and soil monitoring networks.

Yusof et al [33] statesthis research investigates spectroscopy for quick soil macronutrient analysis with a Deuterium-Halogen light source and an Ocean Optic spectrometer. Absorbance values of N, P, and K were measured in various soil samples, determining peak wavelengths for each of the nutrients. Future research will focus on creating a low-cost LED-based optical system for soil spectroscopy.

Ramane et al [34] says that the color sensor in the form of a fiber optic is utilized to inspect the nitrogen (N), phosphorus (P), and potassium (K) levels in the soil based on its color. It informs whether they are in high, medium, low, or absent quantity. This assists farmers in using only the required fertilizers, thus making the soil healthier and crops improved.

Sørensen et al [35] statesthat portable NMR sensor is created for online analysis of nitrogen (N), phosphorus (P), and potassium (K) in animal manure. Based on a 1.5 T Halbach magnet, it measures the most important nutrients directly, avoiding rough estimates or time-consuming laboratory tests. The sensor gives precise data, comparing well with industrial laboratory measurements.

SV, M. G., &Galande et al [36] statesan advanced wireless sensor network (WSN) is developed to monitor agricultural field soil nutrient (NPK), pH, temperature, and humidity. WSN is applied to assist farmers with optimal fertilization and irrigation using the provision of real-time data from WiFi sensor nodes. This improves the utilization of resources, prevents over-fertilization, and supports increased crop production.

| **Paper Title** | **Sensor Type** | **Measurement Principle** | **Calibration Method** | **Limitations** |
|---|---|---|---|---|
| Coutinho et al [28] | Vis-NIR, Mid-Infrared Spectroscopy | Spectroscopy-based soil fertility analysis | Standardized spectroscopic calibration | High prediction error limits practical application |
| Monteiro-Silva et al [29] | Optical (UV-Vis Spectroscopy) | Absorption spectra with AI-based correction | Self-learning AI algorithm for spectral interference correction | High spectral interference, low P and K accuracy in conventional models |
| Nameesha Chauhan et al [30] | Electrochemical | Ion-selective electrode (ISE) & Ion Selective Field-Effect Transistor (ISFET) | Flow Injection Analysis (FIA) for electrochemical sensing | Response time limitations, environmental dependencies |
| Masrie et al [31] | Optical (LED-Photodiode System) | Light absorption by nutrients using LEDs and photodiodes | Tested with varying optical path lengths | Requires optimization of LED-photodiode distance |
| Liu et al [32] | Optical (Colorimeter) | Beer-Lambert's Law | Standard solutions (20 ppm) | Ambient light interference, potential signal loss |
| Yusof et al [33] | Spectroscopy-based sensor | Light absorption at specific wavelengths for NPK detection | Uses Deuterium-Halogen light source and Ocean Optic spectrometer | Limited to non-agriculture soil; high-cost spectrometer |
| Ramane et al [34] | Optical (Fiber Optic Sensor) | Colorimetric measurement of aqueous soil solution using fiber optic probe | Standard color chart comparison | Limited by soil sample preparation and environmental factors |
| SV, M. G., & Galande et al [36] | Wireless Sensor Network (WSN) | Uses multiple sensors for detecting soil parameters | Requires periodic recalibration of soil sensors | Connectivity issues in remote areas, potential sensor drift |
| Sørensen et al [35] | Nuclear Magnetic Resonance sensor | Uses 14n,17o,31p&39k nmr for direct detection of ammonium N,total P & K | No user side calibration required | Sensitivity challenges with quadrupolar nuclei,large magnet requirement |

**CONCLUSION**

This review summarizes the strengths and weaknesses of some NPK soil sensors in terms of their performance, durability, and IoT connectivity. Highest Accuracy: Electrochemical sensors (ISE, ISFET) have high accuracy but need frequent calibration, while optical sensors (spectroscopy, colorimetry) provide fast, non-destructive measurements but are affected by soil content.

Most Durable: Capacitive and conductivity sensors are durable and long-lasting, yet biosensors have a limited lifespan even though they possess better selectivity. Ideal for IoT & AI: Though electrochemical and optical sensors are suitable for smart agriculture, WSNs provide for large-scale real-time monitoring. To realize maximum precision agriculture and environmental sustainability, upcoming research must target improving sensor durability, enhancing AI calibration, and integrating multi-sensor networks.

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